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*INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-Third International Workshop*

Development of Methods to Investigate the Effects of Knee Angle and Quadriceps Tendon Tension on Patella Kinematics and Knee Fracture Tolerance Due to Knee Bolster Loading in Frontal Impacts

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ABSTRACT

The majority of biomechanical tests that have been conducted to study knee injury tolerance and response in frontal crashes have used rigid or thickly padded flat-surfaced impactors that impact the anterior surface of the 90-degree flexed cadaver knee in a direction parallel to the long axis of the femur and without simulation of muscle tension. However, these impact conditions are not representative of typical knee-bolster-to-knee loading conditions in frontal crashes of today's airbag-equipped vehicles. Laboratory tests are therefore being conducted to investigate the effects of knee angle and quadriceps muscle tension on knee response and knee injury tolerance as part of a larger study to characterize the response and tolerance of the knee, thigh, and hip to knee loading conditions that are representative of knee interactions with knee bolsters in frontal crashes of airbag-equipped vehicles. To determine representative knee angles and angles of the impactor surface relative to the femur, computer simulations of occupant kinematics in frontal impacts were performed using vehicle package geometry and occupant posture data from other UMTRI studies. In addition, tests were performed to determine the area over which forces are distributed across the knee during knee-to-knee-bolster interaction during frontal crashes by impacting Hybrid III ATD knees into the surface of production knee-bolsters. Based on these results, the impactor surface is angled at either 15 or 25 degrees from vertical and is padded to produce a contact area similar to that of the contact area between the Hybrid III knee and a production knee bolster. Isolated tibia-knee-femur specimens are prepared for testing by fixing the truncated ends of the femur and tibia in epoxy resin. The potted femur and tibia are then rigidly secured in the test fixture such that the long axis of the femur is horizontal and aligned with the direction of impactor motion. Pilot testing was conducted in which the effects of knee angle and quadriceps muscle tension on knee tolerance were explored while simultaneously exploring the effects of a knee-bolster-like loading condition on the response of the cadaver knee. Pre-impact tension in the quadriceps femoris tendon is set to either 5% or 50% of the estimated maximum force-producing capability of the thigh flexors by means of a cable parallel to the long axis of the femur attached to a force-limiting pneumatic actuator. In addition to

measuring the applied force history, the response of each specimen was monitored using high-speed video and high-speed x-ray, where the latter provides information on patella kinematics and timing of knee fractures during impact loading. Preliminary results show that the type of knee fracture produced is related to the position of the patella at the time of fracture, with patella fractures occurring more often when the patella is above the center of the femoral condyles, and split condylar fractures occurring when the patella translates downward into the intercondyloid notch. Use of an impactor surface that is angled relative to the long axis of the femur increases the tendency for downward movement of the patella into the femora notch. However, the amount of downward patella movement is also affected by the initial patella position, which is a function of knee angle, and by the level of quadriceps muscle tension.

INTRODUCTION

An analysis of the National Automotive Sampling System (NASS) from 1995-2000 by Rupp et al. (2002) reports that annually in the United States, approximately 30,000 occupants sustain AIS 2+ injuries to the knee-thigh-hip (KTH) complex due to automotive frontal crashes. Of these injuries, approximately 8000 occur to the occupants' knees, and include injuries to the patella, femoral condyles, and knee ligaments. It has been estimated that in the United States the cost of these knee injuries exceeds \$1.75 billion annually (Blincoe et al., 2002; Kuppa and Fessahaie, 2003).

Current KTH injury criteria adopted by the Federal Motor Vehicle Safety Standards (FMVSS) state that the axial femur loads measured by an anthropomorphic test device (ATD) must not exceed 10 kN during new vehicle certification. This injury criteria is based on research performed during the late seventies and early eighties by Powell et al. (1975), Melvin and Stalnaker (1976), Melvin and Nusholtz (1980), and Patrick et al. (1965), which measured the tolerance of the KTH by impacting the knees of whole embalmed and unembalmed cadavers using either rigid or heavily padded impactors.

The effects of impactor compliance and tibia-to-femur angle on patellofemoral joint contact pressures and knee fracture patterns and tolerance was studied by Haut (1989). In this study, paired testing was conducted on isolated knee specimens from eight unembalmed cadavers across a range of femur-to-tibia angles. One knee from each cadaver was impacted with a flat rigid impactor that applied a focal load to the surface of the patella, while the other knee was impacted by a compliant impactor that distributed impact forces across the surface of the patella and the femoral condyles. Of the six tests in which paired testing was conducted, the average fracture force was 8.4 kN for tests performed with a rigid impactor, and 8.9 kN for test performed with a padded impactor. Due to the limited number of tests performed, the effects of knee angle on the fracture tolerance of the knee are still unknown.

Atkinson et al. (1997) impacted pairs of left and right isolated knee specimens using rigid and padded impactors. One knee from each pair was impacted with a rigid impactor and the contralateral knee was impacted with an impactor padded with an aluminum honeycomb material and impacted with sufficient energy such that the peak loads recorded were similar to those achieved during testing with a rigid impactor. Knee impacts performed with a rigid impactor produced either gross patella fractures or retropatella occult micro cracking in five out of the six subjects tested, while impacts performed with a padded interface resulted in no observable knee injuries. These test results show that the injury tolerance of the knee increased when the knee is subjected to a distributed load, but the fracture tolerance of the knee to a padded impactor is still unknown since no fracture producing experiments were performed using a padded impactor.

The purpose of the current research was to determine the knee/femur loading conditions that are representative of knee-to-knee-bolster loading in frontal crashes and to develop test methods in which the effects of knee angle and quadriceps muscle tension on the fracture tolerance of the cadaver knee can be studied. This paper describes the test methodology and the basis for the test conditions used, as well as preliminary results and observations from pilot testing on 11 specimens.

METHODS

Estimating Knee and Knee-Bolster Angles

Variations in knee angle and the angle of the knee bolster relative to the long axis of the femur during frontal crashes were estimated using data previously collected at UMTRI. These data include interior

vehicle package geometry of a 2002 Pontiac Grand Am, a 2000 Ford Taurus, and a 2001 Dodge Caravan that were digitized using a Faro arm. As illustrated in Figure 1, measurements collected included seat track range, steering wheel position, and side view knee-bolster contour forward of the driver's knees. Figure 2 shows an example of driver posture data collected by digitizing body skeletal landmarks of 18 men and 18 women representative of a wide range of stature, after driving for fifteen minutes in each vehicle. These data include the location of the lateral malleolus, the lateral femoral condyles, and the suprapatella, which are used to define the posture of the driver's legs.



Figure 1: Digitized vehicle package geometry of a Ford Taurus (Blue), Pontiac Grand Am (Red), Dodge Caravan (Green).

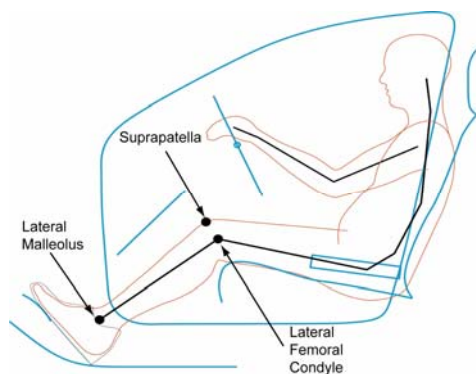


Figure 2: Skeletal landmarks collected in UMTRI studies to define the posture of the driver's legs.

As illustrated in Figure 3, a simple 2-D model of each of the 36 occupants was used to simulate knee-to-knee-bolster interaction by translating the driver's hip forward horizontally while maintaining the foot fixed on the floor and rotating the leg about the ankle joint until the surface of the knee contacted the surface of the knee-bolster. Knee contact was estimated as the intersection of the point describing the suprapatella landmark and the plane defining the knee-bolster surface. Posture variables including knee angle, femur angle, and bolster-to-femur angle, were calculated at the occupant's initial position, at the point of simulated knee contact, and at an additional 100 mm of horizontal pelvis stroke following knee-to-knee-bolster contact.

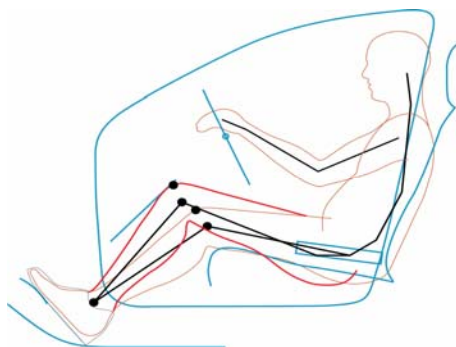


Figure 3: Two-dimensional linkage model of occupant's knee, thigh, leg, and ankle. Bolster-to-femur, knee, and horizontal femur angles were calculated at each occupant's initial position, point of calculated knee contact, and at an additional 100 mm of horizontal hip translation after knee contact.

The results of the knee angle simulations are listed in Table 1 and were used to determine an appropriate range of knee angles that occur during frontal crashes. Based upon these results, knee angles of 70, 80, 90, and 100 degrees were selected for pilot testing to study the effects of knee angle on the fracture

tolerance of the cadaver knee. In addition to these knee angles, pilot tests were also conducted at knee angles of 60 and 120 degrees to determine the response of the knee at angles that fall outside of the selected range.

Table 1. Statistical Knee Angles* Determined by 2D Linkage Model Simulations (n = 36).

Vehicle	Statistic	Starting Angle (degrees)	Contact Angle (degrees)	100-mm Stroke (degrees)	Change in Angle to Bolster Contact (degrees)	Change in Angle After Bolster Contact (degrees)
Caravan	Mean	117.8	82.2	67.6	-35.6	-14.7
	Min	83.2	57.5	49.5		
	Max	140.1	102.3	85.2		
Grand Am	Mean	126.7	99.4	81.0	-27.3	-18.3
	Min	101.4	58.3	42.5		
	Max	147.9	118.6	97.2		
Taurus	Mean	119.1	94.0	76.5	-25.0	-17.6
	Min	93.1	71.0	55.7		
	Max	139.4	115.1	96.4		
All	Mean	121.2	91.9	75.2	-29.3	-16.6
	Min	83.2	57.5	42.5		
	Max	147.9	118.6	97.2		

* Included knee angle in side view; straight knee =180 degrees.

Table 2 lists simulation results for the relationship between the angle of the femur and the angle of the knee-bolster surface during frontal impacts and indicates that at the point of simulated knee-to-knee-bolster contact there is a mean angle of approximately 65 degrees between the femur and the knee-bolster surface. Since mean simulation results do not account for knee-bolster deformation, which could result in a change in the angle between the knee-bolster surface and the occupants thigh during loading, two impactor orientations of 65° and 75° were selected to study the effects of impactor orientation on the response of the knee during impact. The orientation of both of these impactor surfaces is such that, over the selected range of knee angles, only the patella is loaded.

Table 2. Statistical Bolster-to-Femur Angle* Determined by 2D Linkage Model Simulations (n = 36).

Vehicle	Statistic	Starting Angle (degrees)	Contact Angle (degrees)	100-mm Stroke (degrees)	Delta To Contact (degrees)	Delta Through Stroke (degrees)
Caravan	Mean	63.1	67.4	67.5	4.3	0.1
	Min	52.5	50.9	53.1	-1.6	2.2
	Max	75.7	77.1	78	1.4	0.9
Grand Am	Mean	57.3	63.4	66.6	6.1	3.2
	Min	47.2	53.2	52.9	6	-0.3
	Max	69.2	78.3	78.4	9.1	0.1
Taurus	Mean	58	63.3	65.9	5.3	2.6
	Min	42.9	47.6	49.3	4.7	1.7
	Max	67	74.1	77.8	7.1	3.7
All	Mean	59.5	64.7	66.6	5.2	1.9
	Min	42.9	47.6	49.3	4.7	1.7
	Max	75.7	78.3	78.4	2.6	0.1

* Angle of bolster with respect to femur. 90° is perpendicular.

Estimating Knee-Bolster Stiffness

To characterize the stiffness of typical knee-bolsters in late-model vehicles, dashboard assemblies from three late-model vehicles were obtained and impacted by the knees of the Hybrid III ATD. Information describing each vehicle dash assembly is listed in Table 3. Tests of driver and passenger knee bolsters were performed separately by partitioning each dash assembly into driver and passenger sections. During the partitioning of each dash assembly, the integrity of each knee-bolster was maintained by sectioning the dashboard at a location that left the knee-bolster and its surrounding structure intact.

Table 3. Vehicle Knee Bolster Information.

Bolster Number	Manufacture	Model	Year	Position	
				Driver	Passenger
1	Ford	F150	1998		X
2	Honda	Accord	1998	X	X
3	Honda	Odyssey	2001	X	X

Each dashboard/knee-bolster section was rigidly supported by mounting the cross-car beam, which serves as a connection between the dashboard and vehicle's frame, to the test fixture as illustrated in Figure 4. To conduct the tests, two Hybrid III midsize-male knees were rigidly mounted to a linearly translating impact sled weighted to 52 kg. The impact sled was accelerated to a closing velocity of 4.0 m/s by means of a pneumatic linear actuator. For all impacts, the knee bolster was symmetrically loaded by the two knees with the direction of impact perpendicular to the knee-bolster surface. Displacement of the sled was measured by a string potentiometer attached between the test fixture and the back of the impact sled. Forces applied to each knee were measured by two 6-axis hybrid III femur load cells located immediately behind the knees. Force measurements were used to insure that applied forces, loading rates, and loading durations were similar to those measured during FMVSS 208 testing. During each test, side view high-speed video cameras

recorded the impact at 1000 frames per second and were used to observe the general manner of knee-bolster deformation.

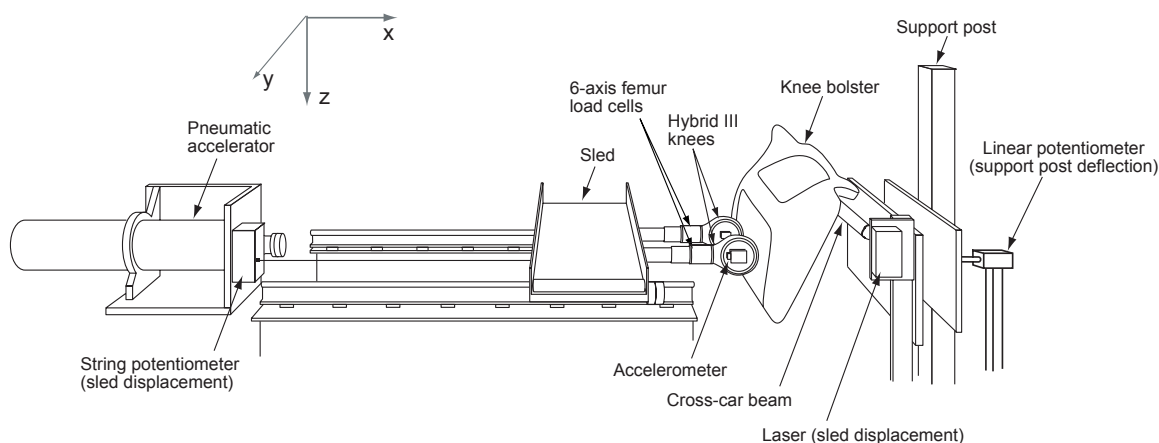


Figure 4: Drawings of test fixture for determining knee-to-knee-bolster contact area.

As shown in Figure 5, contact area between the surface of the Hybrid III midsize male knees and the surface of the knee-bolster during impact was measured by applying blue dye to the knee-bolster surface prior to impact. Immediately following each test, images of the dye pattern transferred to the surface of each knee were recorded as shown in Figure 6. Using image analysis software, the pattern of dye transferred to each knee was outlined and used to determine the area of contact.



Figure 5: ATD knees in front of production knee-bolster showing blue dye applied to surface of knee bolster at the locations of knee impacts.

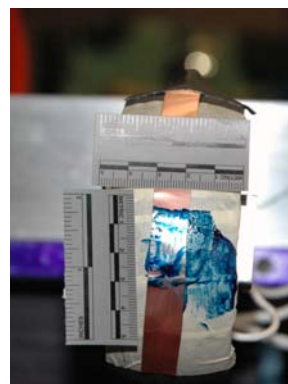


Figure 6: Recorded image of blue dye on ATD knee used to calculate area of knee-to-knee-bolster contact.

The results of the measured contact area between the hybrid III knee and the knee-bolster surface are listed in Table 4 and were used to develop an impactor interface for use in knee tolerance testing. The resulting contact areas range from 9 to 23 cm² with an average area of 14 cm². Using these results, a lightly padded ½" thick impactor interface consisting of 70 durometer Shore A Buna-N rubber was chosen, that when impacted into the Hybrid III knee produces a contact area similar to the mean area of 14 cm² produced by production knee bolsters.

Table 4. Area of Contact Between Hybrid III Midsize-Male Knees and Knee-Bolster Surface.

Bolster Number	Knee Contact Area (cm ²)			
	Driver		Passenger	
	Right	Left	Right	Left
1	NA	NA	9	10
2	15	16	11	15
3	23	20	9	9
Average (min-max)	14 (9-23)			

Test specimen preparation

All tests were performed with isolated knee specimens obtained from unembalmed cadavers. When sectioning the cadaver to obtain the knee specimen, reference marks were applied to the thigh and leg to insure that the orientations of the knee specimens could be referenced back to the orientations of the whole femur and tibia in situ. To prepare the specimen for potting, flesh was removed immediately proximal and distal of the knee joint, and the femur truncated approximately 18-cm proximal of the center of the femoral condyles, and the tibia/fibula truncated approximately 14-cm distal of the center of the tibial plateau. The truncated femur was inserted into the center of a 7.6-cm diameter rigid metal cup that was filled with room temperature curing epoxy to a depth that left the distal femur exposed approximately 12-cm. A similar procedure was used to pot the tibia and fibula 10-cm distal of the tibial plateau.

An array of three 1-mm diameter radio opaque markers, spaced 6.4-mm apart, were inserted into the lateral face of each the patella, femoral condyles, and tibial plateau as show in Figure 7. Markers were inserted into the knee joint through three small incisions. During marker insertion, all attempts were made to limit damage to the knee joint capsule. Patella markers were inserted into three small indentations created in the bony surface of the patella, and secured with an instant curing adhesive. Femur and tibia markers were inserted into 1-mm diameter holes drilled to a depth that placed the markers in the same sagittal plane as those inserted into the patella. During testing, no fractures occurred near any of the drilled holes.



Figure 7: Pretest x-ray of knee specimen showing insertion of 1-mm radio opaque markers inserted into the patella, femoral condyles, and tibial plateau.

Test Configuration

To minimize inertial effects, each specimen was fixed to the test fixture by clamping the potted ends of the femur and tibia into 7.6-cm diameter metal collets, as illustrated in Figure 8. Each test specimen was aligned so that the femur was horizontal and parallel to the direction of impactor loading. To vary the angle of the knee between tests, the vertical orientation of the collet securing the tibia was adjusted while keeping the femur horizontal. During impact, the angle between the femur and tibia remained fixed.

Quadriceps tendon tension is generated immediately prior to and during testing in a manner similar to that described by Meyer and Haut (2003). As illustrated in Figure 8, tension is applied to the quadriceps tendon by a pneumatic actuator attached to a cable that was coupled to the quadriceps tendon by means of a tendon clamp, with tendon forces applied along the line of action of the quadriceps femoris muscle. Muscle tension levels are maintained during impact by regulating the pressure applied to the pneumatic actuator. Levels of tension were selected to represent approximately 5% (250 N) and 50% (2500 N) of the maximum static force-producing capacity of the thigh flexors (Wickiewicz et al., 1983) and dynamic tension in the cable was measured using a uniaxial load cell.

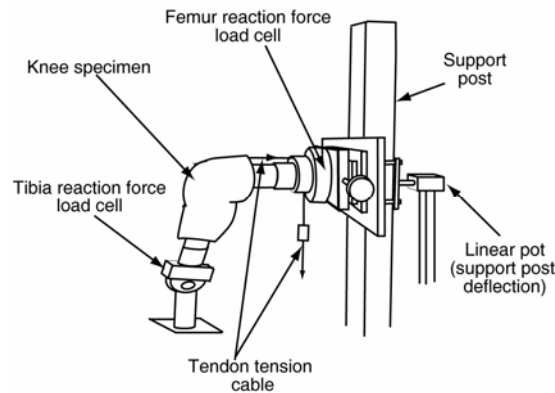


Figure 8: Illustrated knee test specimen rigidly secured to test fixture.

The impact load is applied to the anterior surface of each knee by accelerating a 250-kg platform into a linearly translating ram connected to a lightly padded angled impactor as illustrated in Figure 9. The impactor is angled at either 15 or 25 degrees from vertical, (i.e., 75 or 65 degrees from femur). A platform velocity of approximately 1.6 m/s is used to produce loading rates between 200 and 1000 N/ms, which is similar to those measured by Hybrid III femur load cells during FMVSS 208 compliance testing of newer model vehicles (Rupp et al., 2002).

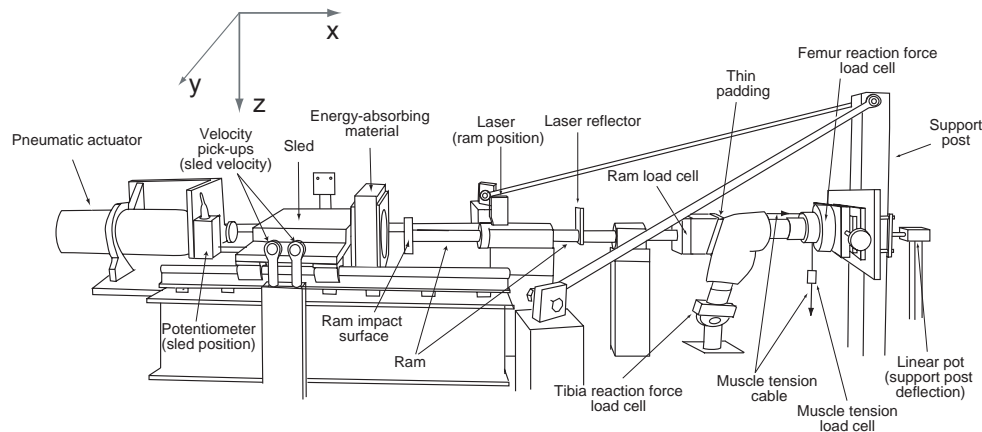


Figure 9: Drawing of test fixture.

Applied forces are measured by a three-axis load cell located immediately behind the impactor. Forces produced at the surface of the impactor are calculated by inertially compensating the measured loads using measured ram accelerations and the known impactor mass between the load cell center-of-gravity and the impactor surface. Reaction forces are measured by a 6-axis load cell positioned immediately behind the femur potting cup, and by a 3-axis load cell positioned immediately below the tibia potting cup. The displacement of the ram relative to the test fixture was measured by a laser-based displacement transducer.

High-Speed X-ray Analysis

The kinematics of the skeletal components of the knee during each test are monitored in the sagittal plane by a digital imager operating at 1000 frames per second which records images produced by a high-speed planar x-ray and image intensifier. As shown in Figure 10, the recorded x-ray images include the patella, distal femur, and tibial plateau, with the center of the x-ray source and image intensifier aligned with the center of the femoral condyles. Three lead markers are placed in a line in each skeletal component of the knee and are visible during all recorded frames of impact.

Following each test, the knee specimen is removed from the test fixture and replaced by a calibration grid positioned in the same sagittal plane as the test specimen. A recorded x-ray image of the calibration grid is used to scale x-ray images recorded during impact. Outlines of the femoral condyles, tibial plateau, and patella are digitized using the first high-speed x-ray image recorded during impact. Relative kinematics of the skeletal components of the knee during impact are obtained from the digitized locations of the lead markers, and are used to graph knee joint kinematics as shown in Figure 11. X-ray images recorded during impact are also used to document the time of knee fracture relative to force signals and the locations of initial fractures.

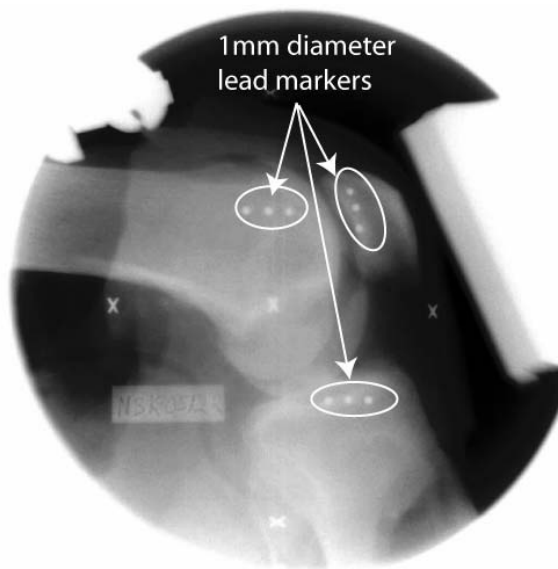


Figure 10: High-speed x-ray image showing 1-mm diameter lead markers inserted into patella, femoral condyles, and tibial plateau.

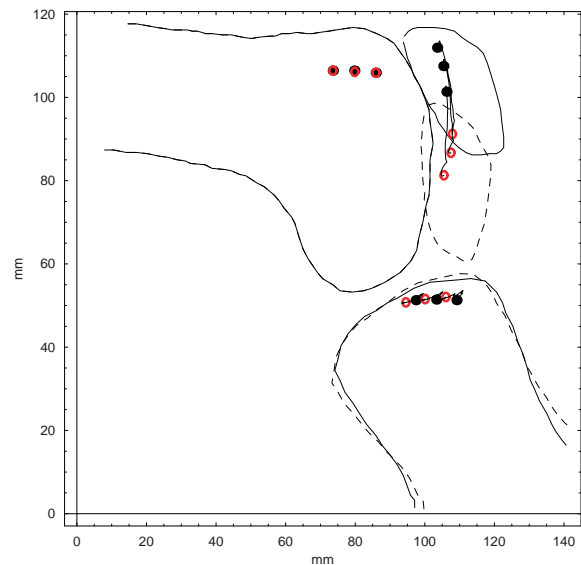


Figure 11: Skeletal components of the knee joint at time of impact (solid lines), and one frame prior to knee fracture (dashed line).

RESULTS

Effects of Knee Angle on Patella Location and Kinematics

Results from preliminary testing conducted over a range of femur-to-tibia angles show that the initial position of the patella relative to the femoral condyles is affected by the angle of the knee, and that the kinematics of the patella are affected by its initial position. As illustrated in Figure 12, large knee angles result in a high initial position of the patella that places the patella above the intercondyloid notch, while acute knee angles result in a low initial position of the patella relative to the femoral condyles. During testing in which the patella was initially high on the femoral condyles, downward patella movement at time of fracture was relatively small. When the patella initially occupied a position low on the femoral condyles there was significant downward patella movement so that the patella was positioned within the intercondyloid notch at time of fracture.

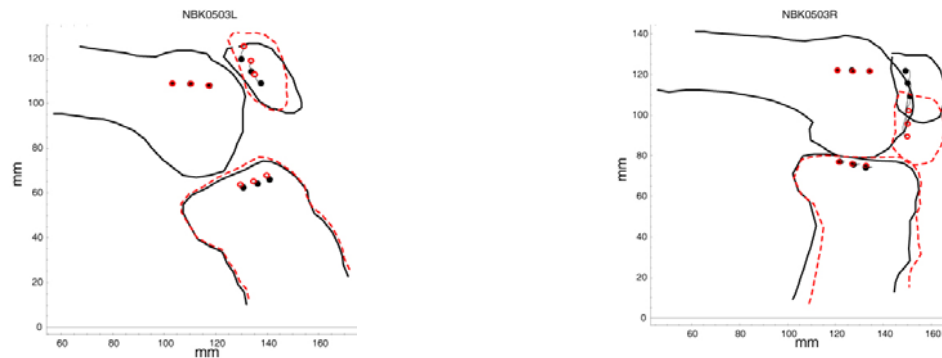


Figure 12: Large knee angle (left) places the patella high on the femoral condyles and results in relatively small downward movement of the patella. Small knee angles (right) place the patella lower on the femoral condyles and allow the patella to translate downward during impact.

Effects of Quadriceps Tendon Tension on Patella Kinematics

Figure 13 shows the effects of quadriceps muscle tension. The low level of quadriceps tendon tension allowed the patella to translate downward during impact into the intercondyloid notch, while the high level of quadriceps tendon tension kept the patella essentially in its initial position.

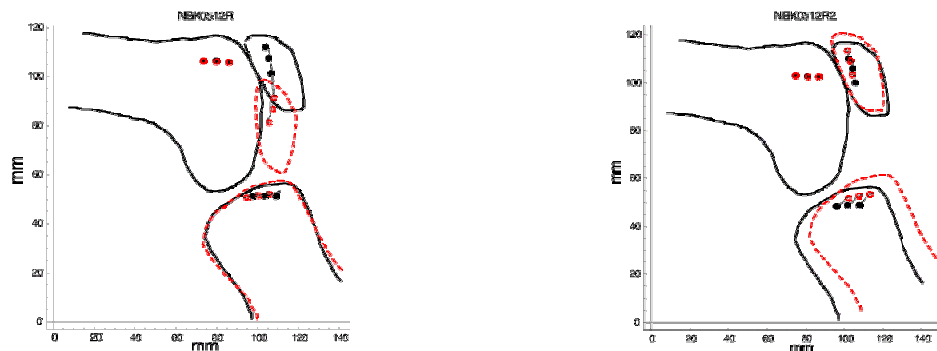


Figure 13: The low level of quadriceps tendon tension (left) allowed the patella to translate downward into the intercondyloid notch during impact. The high level of quadriceps tendon tension (right) prevented downward movement of the patella during impact loading.

Effects of Patella Location on Type of Knee Fracture

Table 5 describes the relationship between the location of the side view geometric center of the patella above or below the side view center of the femoral condyles, and the type of knee fracture produced during pilot testing. For this analysis, the center of the patella and femoral condyles were estimated by digitizing their locations from high-speed x-ray images recorded during knee impact. The mean distance between the center of the patella and the center of the femoral condyles is plotted in Figure 14, and shows that on average, patella fractures occurred when the patella was approximately 11-mm above the center of the femoral condyles, while split condylar fractures occurred when the patella was approximately 11-mm below. These results suggest that the type of knee fracture sustained is related to the kinematics of the patella during impact. As illustrated in Figure 15, during tests in which the patella occupied a high position on the femoral condyles above the intercondyloid notch, there was an increased likelihood of producing patella fractures. Alternatively, when the patella occupied a position low on the femoral condyles and was inside of the intercondyloid notch (as shown in Figure 16) at time of fracture, a split condylar fracture was usually produced.

Table 5. Location of Patella at Fracture and Type of Knee Fracture.

Test ID	Location of Patella at fracture (mm)*	Type of Knee Fracture
NBK0503L	18.4	Patella
NBK0503R	-21.1	Split condylar
NBK0504L	8.0	Split condylar
NBK0505R2	3.3	Patella
NBK0506R	11.8	Patella
NBK0507L	-24.0	Split condylar
NBK0507R	-14.2	Split condylar
NBK0508L	-11.5	Split condylar
NBK0510L	-14.7	Split condylar
NBK0510R	0.0	Split condylar

* Vertical distance between center of patella and femoral condyles (positive values represent patella above center of femoral condyles, negative values below).

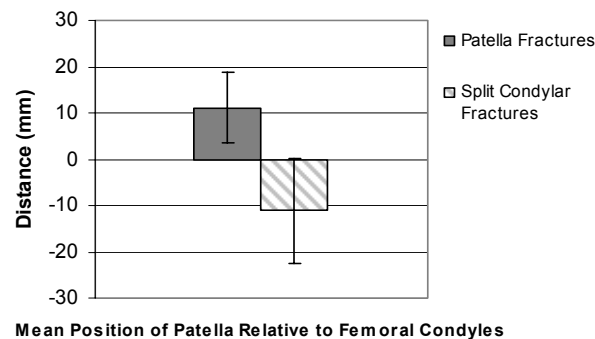


Figure 14: Mean location and \pm one standard deviation of the center of the patella above or below the center of the femoral condyles for tests producing patella and split condylar fractures. Positive values represent a patella position above the center of femoral condyles; negative values represent a patella position below the center of femoral condyles.

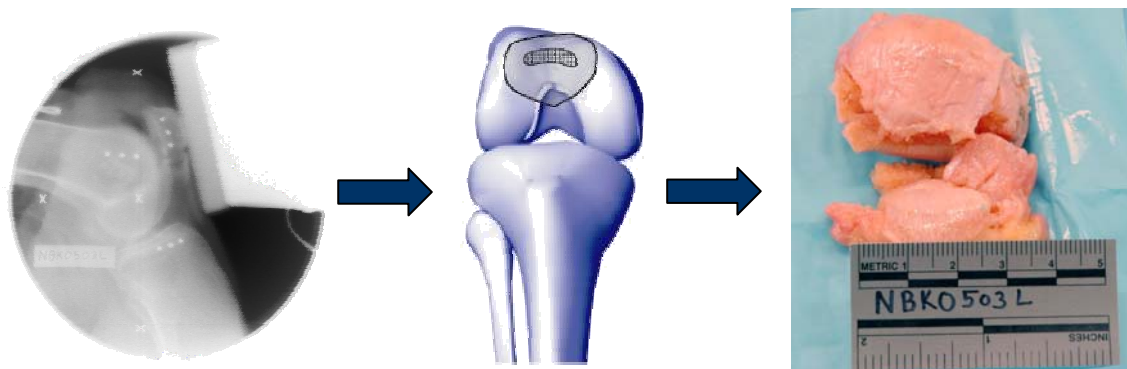


Figure 15: A patella positioned high on the femoral condyles at time of knee fracture centers the patella-femur contact area which tends to lead to a fractured patella.

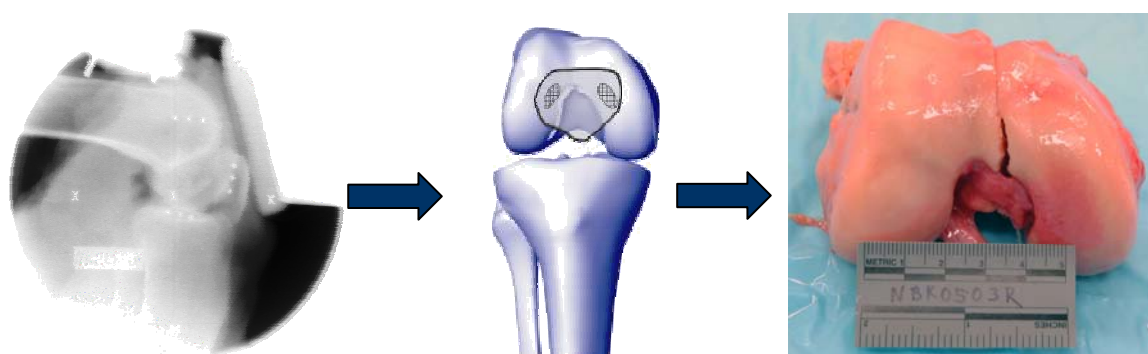


Figure 16: A patella positioned low on the femoral condyles places the patella within the intercondyloid notch, allowing the patella to act as a wedge, and leads to an increased risk of split condylar fractures.

DISCUSSION

The purpose of this study was to develop methods to investigate the effects of knee angle and quadriceps tendon tension on knee fracture tolerance and knee fracture pattern to FMVSS 208-like loading conditions. Simulations were performed using vehicle package geometry and occupant posture from other UMTRI studies to estimate representative knee angles during frontal crashes. The results of these simulations indicate that knee angle varies over a wide range due to differences in vehicle package geometry, occupant size, and occupant positioning. Simulation results also suggest that, at the point of knee-to-knee-bolster contact, the average initial angle between the knee-bolster surface and the occupant's thigh is 65 degrees, which is substantially different than the perpendicular impact conditions used in most previous biomechanical studies. Results of pilot testing conducted with a horizontal femur and an impactor surface that is 25-degrees to the vertical (i.e. 65 degrees to femur), demonstrate that the angled impactor changes the direction of force applied to the knee and increases the likelihood of producing downward patella kinematics compared to testing conducted with a vertical impactor.

For all tests conducted using the 65-degree impactor-to-thigh angle, no loading of the tibia occurred prior to knee fracture. This is in contrast to most previous biomechanical tests conducted with a 90-degree flexed knee and an impactor surface that is perpendicular to the long axis of the femur, which result in both patella and distal tibia loading. The angled impact surface is believed to be more representative of knee loading conditions in frontal crashes of production vehicles for which knee ligament injuries are relatively rare.

Preliminary results suggest that the type of knee fracture and the associated fracture tolerance are related to the position of the patella at the time of fracture. There are several factors that affect the latter, including the initial position of the patella, which is a function of individual joint morphology and knee angle, the level of quadriceps tendon tension, and the angle of the impacted surface relative to the knee and thigh. Since split condylar fractures rarely occur as a result of knee-to-knee-bolster loading during real-world frontal crashes, this suggests that during frontal impacts either the patella rarely gets into the notch between the femoral condyles, or the forces are low enough as to not cause a fracture under knee-bolster-like loading. Since the impactor-to-femur angle and the force deflection characteristics of the impactor surface used during this study are thought to be a better representation of real-world knee loading conditions, this suggests that quadriceps muscle tension is very important in the real-world and needs to be included in studies on the fracture tolerance of the cadaver knee.

CONCLUSIONS

This study developed a test methodology and experimental test setup, and established baseline test conditions, that can be used to investigate the effects of knee angle and quadriceps femoris tendon tension on the fracture tolerance of the human knee-to-knee-bolster loading in frontal crashes. A range of knee angles between 70° and 100° was identified and an average angle of 65° between the surface of the knee-bolster and the long-axis of the femur has been identified. Results of tests conducted to date indicate that patella kinematics and position (relative to the distal femur) during impact loading are related to the initial position of the patella, the level of applied quadriceps muscle tension, and the orientation of the impactor surface relative to the femur. The initial position of the patella is, in turn, a function of knee angle and individual joint morphology, and knee angle during loading is a function of vehicle package geometry and occupant position.

ACKNOWLEDGEMENTS

This research was supported by the National Highway Traffic Safety Administration under contract number DTNH22-05-H-01020.

The authors are grateful of the efforts of Thomas Jeffreys for his assistance during testing and for his preparation of test specimens. The authors would also like to acknowledge the efforts of Brian Eby and Jim Whitley for their development of test fixtures used in this research.

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DISCUSSION

PAPER: **Methods to Investigate the Effects of Knee Angle and Quadriceps Tendon Tension on Patella Kinematics and Knee Fracture Tolerance Due to Knee Bolster Loading in Frontal Impacts**

PRESENTER: ***Carl Miller, University of Michigan Transportation Research Institute***

QUESTION: *Akira Kanatani, Toyota*

Thank you for interesting presentation. I'm actually conducting the similar study using FEM model and I always saw the patella moves downward during, while I'm pushing the knee. Today, I realized that that was because I don't have any vascular effect in the quadriceps muscle. So, thank you for information!

ANSWER: You're welcome.

Q: And my question is: Did you take a look at the force displacement curve with and without muscular tension or different force level because I expect some...I expect that you will have some little bit more space if you can move the patellar downward.

A: Yes, I believe you're correct. In a test where, you know, we specifically—Well, we have some measurements of the displacement of the RAM relative to the knee. But as far as pulling stiffness data directly from that, you have the rigidity of the impact surface that somewhat affects that. But I believe you are correct that if you see motion of the patella, that'll reduce the stiffness.

Q: Okay. Thank you.

A: You're welcome.

Q: *Guy Nusholtz, Daimler Chrysler*

Your legs are fixed.

A: Um hmm.

Q: And, have you considered the affect of the bodily condition that you're setting up? In addition, the dynamic impact into a knee bolster, you have a changing angle, both of the femur and the tibia and that could have quite a dynamic affect on your results. So then, have you considered a way to try and mimic that or see if, how important that is in the actual response that you're trying to measure in terms of both the dynamics and the injury response?

A: Yeah. That's a factor that we have identified that, you know, can play a role. Specifically for this research we want to control for knee angles so changing knee angle during the test, if you're using it as a controlled variable, may not be practical, but I believe you are right that there is some relationship that's going to change the position of the patella as the knee flexes during impact.

Q: Well, the question that I would have—The point is that that may overshadow what the initial angle is and it may end up being more important.

A: Correct. I mean, what we may find is that it's the actual position of the patella at the time of fracture that is really the important factor, not the initial position of the patella.

Q: Thank you.

A: You're welcome.

Q: *Uwe Meissner, Volkswagen*

I want to continue what Guy said. During the impact in an energy management system, the knee barrel deforms so you have a continuously changing angle there.

A: Um hmm. Correct.

Q: So, the question is: When does the fracture occur? When you bottom out with the energy movement there?

A: Well, we believe the fracture's going to occur before the time of peak force, at least in, you know, our tests. And, you're right—Go ahead.

Q: In your test, you have a, let's say, rigid impact except for the—

A: Light padding.

Q: Light padding. But in a real car, the knee bar will deform.

A: Um hmm.

Q: So you don't get to the—or at least, you don't get to the initial high force in the beginning, I believe.

A: Until you get to bottom.

Q: Until you bottom.

A: This is something we'd referenced specifically. If you see in our test matrix—I can't find my mouse. Okay. There we go. In our test matrix, you can see that we've skewed the angles so that they're, represent more acute in the angles and this is to address the fact that we believe as the knee penetrates into the bolster, we'll see a reduced knee angle. That's kind of our way of looking into that factor.

Q: *Erik Takhounts, NHTSA*

I wonder if you look—if you thought about how your muscle activation would affect not just knee injuries but hip injuries, for instance. You may win in one place but lose in another.

A: Well, correct. I mean, we don't want to protect the knee at the risk of injuring the hip. Typically we're trying to look at, you know, what is the factor tolerance of the knee specifically and not necessarily how it relates to the hip, in this particular study. As part of our overall research goal, we want to combine all these individual fracture tolerances of each component and be able to create the model of the overall KTH complex.

Q: Okay. Thanks. Good.